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ABSTRACT

A great deal of experimental and theoretical effort is underway to use neutrinos as a probe for Physics Beyond the Standard Model. Most of these efforts center on the questions of the possible existence of non zero neutrino mass and mixing. Sessions at the Moriond conferences have dealt with these questions at most of the meetings during the last several years and this year was no exception. Presentations covering most of the current and planned research in this field were presented and discussed. Although there is, at present, no definitive evidence for a non zero neutrino mass and mixing, several unresolved problems (in particular solar neutrinos) do seem to be indicating the likely existence of new neutrino properties. It is likely that before the end of this decade, efforts now being initiated will be able to determine whether or not the hints we are now seeing are really due to new physics.

INTRODUCTION

Neutrinos play a dominant role in both particle physics, astrophysics, and cosmology. In the our present understanding of the strong, weak, and electromagnetic forces, the group structure of the Standard Model is $SU(3)_C \otimes SU(2)_L \otimes U(1)_{EM}$. In the Weinberg-Salam-Glashow Standard Electroweak Model, left-handed neutrinos are in a doublet, while right-handed neutrinos are in a singlet, and therefore do not interact with the other known particles. In this model, the neutrinos are intrinsically massless and conserve lepton number. However, while the W-S-G provides an amazingly accurate picture of our present cold Universe, it has a number of deficits. The Standard Model does not explain the origin of the group structure, it does not reduce the number of coupling constants required, nor does it offer any prediction for the physical masses of the particles. Thus, it is generally assumed that the Standard Model is but a subset of some larger gauge theory. A wide variety of Grand Unified field Theories (GUTs), Super Symmetric Models (SUSY) and Superstring models have been proposed as the model for this larger structure. In general, these models predict non zero neutrino masses and contain mechanisms that provide for lepton-number violation. Thus, a variety of new phenomena are predicted, including finite neutrino masses and the possibility that neutrinos can oscillate from one type to another.

In astrophysics, neutrinos play direct roles in the energy-producing reactions in stars, as well as being the primary driving force in supernova explosions. As the cross sections for neutrinos are so small (typically 10^{-40} cm^2), they generally do not interact as they exit a star and thus they can provide a direct means of probing the stellar interior. In contrast, the energy we observe radiated from stars takes of order 10^6 years to reach the surface of the star and suffers so many interactions that any direct information is lost.

Finally, in Standard Big Bang cosmology, the number density of relic neutrinos is comparable to that of photons, and is therefore of order 10^9 times higher than that of baryons. Thus, if neutrinos have even a very small mass (of order a few tens of eV), they will be the dominant form of matter in the Universe and may be an explanation for dark matter. Even with masses of only a few eV, they will strongly influence the large scale structure of the Universe

STATISTICAL AND SYSTEMATIC CONCERNS IN SEARCHES FOR NEW PHYSICS

In searching for new physics beyond the Standard Model, one is usually looking for rare phenomena or slight deviations from an expected shape. It is extremely important in carrying out such experiments that the statistical and systematic analyses do not bias the results in any way which might either hide a real effect or introduce a spurious effect. Knapp* pointed out the difficulties and problems that one can encounter in doing fairly straightforward statistical analyses of the data. The case in point was analysis of the tritium beta decay experiments, but the point applies equally well to many experiments. In analyzing the tritium data, one has very few events in the region of interest and therefore must use Poisson statistics. However, one can use either the Neyman's or Pearson's fitters, and one finds different results fitting the same data set with the two different fitters. In general Neyman's X^2 underestimates the area fitted while Pearson's X^2 overestimates the area. These effects can lead to an apparent (but spurious) ν_e mass of more than -100 eV^2 to + 40 eV^2. Thus, in general, one must carry out Monte Carlo checks of the fitters and derive an unbiased fitter in order to ensure that the result is correct. Knapp* went on to discuss possible systematic errors which could also affect the results of the tritium beta decay experiments. Many of these ideas apply generally to all experiments, such as the idea that one must take a penalties error of 1-σ every time one tries to fit the same data set under different assumptions or with different cuts when trying to maximize the experimental sensitivity for a particular result when that result is already known from an earlier round of fitting. The moral of the story is that there is a real danger of bias in analyzing data when you already "know" the answer.

BETA DECAY

There are three known flavors of neutrinos: electron, muon, and tau (together with their corresponding antineutrinos). Neutrinos may also be classified as Dirac, in which case the right and left handed neutrinos ν_R and ν_L and their antiparticles ν_R and ν_L are distinct states, or Majorana, in which case ν ν, so that there are only two states ν_R and ν_L. Electron and muon neutrinos have been directly observed in many experiments. The tau neutrino has not yet been directly [illegible]served, but is assumed to exist as it is required in the Standard Model and from LEP results. By observing the beta decay spectra of nuclei, muons, and tau particles, one can kinematically reconstruct the events, and the existence of a finite neutrino mass will produce a well-defined distortion in the spectra.

Tau Neutrino

The best limit on the ν_τ mass comes from the ARGUS collaboration at DESY. By observing the decay of a tau to 5-pion final states, one can constrain the tau neutrino mass by looking for events very close to the endpoint. A total of 20 events has been observed, and coupled with recent new measurements of the tau mass, provides an upper limit of 31 MeV (95% CL).[1] With higher statistics and improved resolution, one might hope to achieve limits of 10 MeV in the future.

Muon Neutrino

The most stringent limit on the ν_μ mass comes from measurements of the μ momentum following the decay of stopped pions. The most recent determination of m_{π^+}, coupled with the muon data of Abela et al[2], gives $m_{\nu_\mu} < -0.097(72)$ MeV, which, using the Bayesian prescription[3], yields an upper limit of 270 keV (90% CL).

However, new measurements at the Paul Scherrer Institute (PSI) of m_{π^+} have resulted in a reevaluation[4] of the Abela et al. data. This results in a new value of $m_{\nu_\mu} < -0.127(25)$ MeV, resulting in a 5-σ negative central value. The difficulty is that m_{π^+} is determined using pionic X-rays and the precision is limited principally by theoretical uncertainties such as electron screening and strong interactions (eg., absorption from the 3d state). Thus, the measurement using stopped pions has a severe systematic problem and cannot be used.

The next best method of determining m_{ν_μ} mass is using π decay in flight in which both the π and μ momenta are directly measured. This method is relatively insensitive to m_π and m_μ. The measurement of Anderhub et al[5] at PSI thus provides the most reliable limit on m_{ν_μ} of $m_{\nu_\mu}^2$ 0.14(20) MeV^2, resulting in an upper limit of $m_{\nu_\mu} <$ 500 keV (90% CL).

Electron Neutrino

Tritium beta decay offers an almost ideal means of searching for a neutrino mass. It is a superallowed decay, the endpoint energy is quite low (18.6 keV), and the atomic final state effects can be well understood. In these experiments, the beta decay spectrum is measured over a wide region far below the endpoint and then the expected spectral shape in the endpoint region is extrapolated assuming a zero neutrino mass and including all effects (energy loss, spectrometer resolution, decay to different atomic final states, backscattering, background, variation of spectrometer acceptance efficiency with energy) that can distort the spectrum. One then measures the spectrum in the endpoint region and compares it with the extrapolated spectrum. A deviation between the extrapolated and measured spectra can be indicative of a finite neutrino mass.

Originally, a Russian group initially claimed to see evidence for a $\overline{\nu}_e$ mass of 35 eV, which was later reduced to 26 eV.[6] Of particular concern in these measurements was the use of a tritiated amino acid (valine) as the source material that required extensive (and somewhat uncertain) theoretical calculations to take into account the atomic and molecular final-state effects. At present, five other experiments have reported results using much simpler source materials, ranging from pure molecular tritium to tritiated molecular compounds.

The measurement of the Livermore group was reported by Stoeffel*. This experiment uses a gaseous T_2 coupled to a magnetic spectrometer. In comparison to the Los Alamos experiment (which used a similar system), the resolution is improved, the backgrounds are lower, and the system can scan over the entire tritium spectrum. Stoeffel reports a limit of 8 eV (95% CL), but also obtains a best fit value with a negative $m_{\overline{\nu}}^2$. It is also interesting that there is a strong surplus of counts at very low energies, below about 1.4 keV. This occurs at about the energy where Simpson saw evidence for a distortion in the T decay spectrum in a solid state detector implanted with T that was interpreted as evidence for a 17-keV neutrino. The Livermore observation may (or may not) be coupled to this. At any rate, this increase was not expected and may be important in trying to resolve the source of the apparent excess of counts near the endpoint.

Bonn* reported on the measurement at Mainz, which uses a frozen T_2 source and an electrostatic spectrometer. This is the first measurement of the tritium beta decay spectrum in which the backgrounds have been sufficiently suppressed in the spectrometer that electrostatic analysis could be used. The spectrometer acceptance is quite high while at the same time the resolution is quite good. The data clearly shows counts due to tritium beta decay to within 20 eV of the endpoint. The quoted limit is $m_{\nu_e} < 7.2$ eV (95% CL). There is one systematic effect which is not yet understood, and which appears to be common to all of the experiments. That is the apparent excess of counts in the region of the endpoint, which results in a best fit value which gives a negative $m_{\bar{\nu}}^2$. In the case of the Mainz experiment, Bonn* reported that this shows up as an apparent 5% branch of some other state at about 75 eV below the endpoint. Further studies of possible sources of this effect are now underway.

Lobashev* reported on the efforts of the group at the Institute for Nuclear Research in Moscow, which will use a gaseous T_2 source coupled to an electrostatic spectrometer. The resolution should be quite good (about 2 eV) with high acceptance from the source. The T_2 source is now being brought into operation, which will then allow one to see if the backgrounds are still acceptably low with T_2 in the source. A goal of this experiment is to be able to measure the beta spectrum below the first excited state in T_2 (at 41 eV) with enough statistics and signal to background that one can search for a non zero neutrino mass without the complications of any excited final states.

As shown in Table 1, all five experiments rule out the ITEP result. However, it must also be noted that all five experiments find a best fit for $m_{\bar{\nu}_e}^2$ which is negative. In fact, the weighted average of the five experiments is $m_{\bar{\nu}_e}^2 = 59 \pm 26$ eV^2. Physically, this corresponds to an observed excess of events in the endpoint region, rather than a deficit, which would be indicative of a finite neutrino mass. Using the Bayesian method, these combined data results in a limit on $m_{\bar{\nu}_e}$ of 5 eV (95% CL). However, as the result is 2.3-σ negative, this limit must be viewed with some suspicion.

Table 1. Limits on the mass of ν_e.

Group	$m_{\nu_e}^2$ (eV^2)	95% CL Limit (eV)
Los Alamos[7]	$-147 \pm 68 \pm 41$	9.3
Zurich[8]	$-24 \pm 48 \pm 61$	11.5
INS Tokyo[9]	$65 \pm 85 \pm 65$	13
Livermore[10]	$75 \pm 41 \pm 30$	8.0
Mainz[11]	$39 \pm 34 \pm 15$	7.2

The origin of the negative central value could be due to either 1) a statistical fluke, 2) an undetermined systematic error in the experiments, or 3) difficulties with the theoretical description of the spectrum. The chance that it is a statistical fluctuation is only 1.2%, assuming that $m_{\bar{\nu}_e}$ is actually zero. An independent check for possible systematic problems has been made by comparing the endpoint measurements from the experiments with the known T-^{3}He mass difference. One finds very good agreement at the few eV level, making it less likely (but not ruling out) that the explanation is a systematic error. However, additional studies of possible effects are clearly warranted and are under way.

Finally, there are two possible uncertainties in the theoretical description of the spectrum. The first is that the effect of decays populating different atomic and molecular final states comes entirely from theory. But in the case of tritium, it is believed that these final-state distributions can be calculated with high accuracy, and in fact several different calculations agree quite well. The other possibility is that some new physics is involved; for example, tachyonic neutrinos, capture of relic neutrinos from the Big Bang, the existence of new particles, etc.. Stephenson* presented the idea that new scalar particles may exist which couple only to neutrinos. The existence of these new particles, if the neutrinos and scalar particles have masses less than about 10 eV, would cause the neutrinos to cluster around matter. This clustering would lead to density enhancements sufficiently large to produce appreciable effects on the neutrino spectrum in tritium beta decay and produce the sort of effect of negative $m_{\bar{\nu}}^2$ observed. Remarkably, the existence of such new scalar particles does not seem to be precluded by any other measurements to date. While it may be that this and other ideas may prove to be ruled out by other data, one should not preclude the possibility that the tritium beta decay experiments are sensitive to new physics, and further theoretical work is merited.

Nonetheless, the use of the Bayesian method provides a relatively stable limit for m_{ν_e}, and it is unlikely that m_{ν_e} can exceed 10 eV. Such a limit not only rules out the ITEP claim, but also eliminates ν_e (or $\bar{\nu}_e$) as the dominant component of dark matter.

17-keV NEUTRINOS

The initial claims of evidence for the existence of a 17 keV neutrino with a few per cent branch in tritium beta decay have been followed by a wide range of subsequent experiments. In these experiments, one observes the admixture of a heavy (17-keV) neutrino with a much lighter (< few eV) neutrino, which results in a kink in the beta spectrum where the beta spectrum with the heavier neutrino kicks in on top of the light neutrino beta spectrum. Physically, in order for this process to occur, not only must the neutrino have a non zero mass, but lepton number must also be violated.

A total of eight experiments claimed to observe evidence for a 17-keV neutrino with a branch of about 0.85%.[12] All of these were remarkably consistent with the best fit to the mass and the branching ratio observed. All were also carried out using solid state detectors. In contrast, more than fourteen experiments (mostly carried out using magnetic spectrometers) claimed not to observe evidence for a 17-keV neutrino with limits on the branching set as low as 0.1% (95% CL).[12]

The most convincing of the experiments observing a 17-keV neutrino are those of Hime and Jelley[13] at Oxford using ^{35}S and ^{63}Ni sources with a solid state detector. An important experiment checking the Oxford results was carried out at Argonne National Laboratory[14] by Freedman* et al using a ^{35}S source placed in the bore of a superconducting magnet. The field profile could be tuned so that as betas spiral along the field lines, their phase space is compressed by the decreasing field so that they strike a solid state detector at the end of the magnet bore at close to normal incidence. Most betas that backscatter from the detector are reflected back by the magnetic pinch effect and are recollected in the detector. This scheme has the advantages of magnetically collimating the betas and of reducing backscattering effects. The results of this measurement observed no evidence for a 17-keV neutrino. This, together with work by Piilonen and Abashian, prompted Hime to reevaluate their data. He carried out careful Monte Carlo calculations of possible scattering effects from intermediate surfaces (such as a thin baffle placed between the source and detector so as to preclude the detector observing betas that might strike the walls of the vacuum chamber). Hime* found that including these intermediate scattering effects could account for the observed distortions in the spectra.[15] This is somewhat surprising, as these effects occur at the one percent level, whereas backscattering and energy-loss effects come in at more than the ten percent level. The backscattering and energy loss effects had been varied in the analysis by a few percent, but they could not account for the observed distortions by any reasonable variation. The problem was that the spectral form of the backscattering and intermediate scattering effects are different, and produce different effects. The new analysis is also in better agreement with the total response function as determined by conversion line measurements. New data from Oxford, as reported by Jelley*, taken with steps implemented to reduce intermediate scattering effects, show no distortions consistent with a 17-keV neutrino.

Additional experiments have also been recently carried out which also do not see any evidence for a 17-keV neutrino. Holzschuh* reported a limit of < 0.1% (95% CL) for a 17-keV branch using a ^{63}Ni source in the Zurich magnetic spectrometer used to study tritium beta decay. An experiment which uses a setup similar to that used at Argonne was reported by Abele*. In this detector, a thin ^{35}S source is placed at the center of the solenoid with detectors at both ends so that all events into 4π are collected. This makes it possible to further suppress the effects of backscattering by adding the energy deposited in both detectors from a backscattered event. The limit determined was a branching ratio for a 17-keV neutrino < 0.5% (95% CL). Thus, while the ^{14}C measurements of the Berkeley group and the tritium data of Simpson still remain unexplained, it is clear that a 17-keV neutrino does not exist with a branching ratio in the fraction of a percent range.

NEUTRINO CROSS SECTIONS

A stringent test of the Standard Model can be carried out by precision measurements of neutrino-electron elastic scattering which provides allows a precise determination of the Weinberg angle. While a number of measurements have been made at accelerators, only one measurement with limited precision has been carried out at a reactor. Thus, Broggini* discussed plans for a new measurement of ν_e elastic scattering at a reactor using a high pressure gas time projection chamber (TPC). In addition, this experiment is designed to search for a magnetic moment of ne with a sensitivity of 2-3 x 10^{-11} Bohr magnetons, which would represent more than an order of magnitude improvement over the current limits.

Other measurements of interest in testing the Standard Model and the structure of the weak interactions have recently been carried out at the ISIS spallation neutron source at the Rutherford Laboratories. Kleinfeller* reported on results from the KARMEN detector of searches for neutrino oscillations and measurements of charged and neutral current interactions in carbon. The data indicate that flavor universality is conserved within 1-σ with an uncertainty of σ = 20% and in general the charged and neutral current cross sections on carbon are as expected, except that there appears to be some discrepancy between measurements at ISIS and Los Alamos of the inclusive charged current cross section on carbon.

DOUBLE BETA DECAY

The pairing force in nuclei results in a number of cases in which beta decay from a nucleus with (Z, A) is not energetically allowed to a daughter with (Z-1, A), but double beta ($\beta\beta$) decay from the (Z, A) parent is energetically allowed to a daughter with (Z-2, A). This can proceed by three possible mechanisms: two ν $\beta\beta$ decay, no ν $\beta\beta$ decay, and no ν $\beta\beta$ decay with the emission of a Majoron. The two ν $\beta\beta$ decay is an allowed second-order process requiring no new physics. No ν $\beta\beta$ decay requires that the neutrino have a mass, that lepton number be violated and that the neutrino is a Majorana neutrino. No ν $\beta\beta$ decay with Majoron emission has, in addition, the requirement that a new particle, the Majoron (a massless Goldstone boson) also exists.

The most stringent limits on the neutrino mass in no ν $\beta\beta$ decay come from the experiments using Ge solid state detectors, which are highly enriched in ^{76}Ge. In this case, the detector is also the sample. The best limit to date comes from a Moscow-Heidelberg collaboration. Piepke* has reported a limit on no ν $\beta\beta$ decay of $< 1.6 \times 10^{24}$ yrs (90% CL). Using calculated nuclear matrix elements, one can then use this result to set a limit on the mass of a Majorana electron neutrino of < 1.2-1.4 eV (90% CL). Larger isotopic ^{76}Ge detectors with lower backgrounds are under construction and one might hope to reach sensitivities of 0.1 eV ultimately.

Similar levels of sensitivity may be reached using other detectors. Busto* reported work on a liquid ^{136}Xe time projection chamber which has provided a limit for no ν $\beta\beta$ of 4.2×10^{23} yrs (90% CL), corresponding to a limit on the Majorana neutrino mass of < 3 eV (68% CL). With anticipated reductions in backgrounds, it seems feasible to reach lifetimes of about 10^{25} yrs.

Some efforts have been made in studies of double positron decay, positron-electron capture decay, and electron capture-electron capture decay as reported by Pomansky*. However, as measurements in ^{85}Kr have only reached lifetimes of $< 2.0 \times 10^{21}$ yrs (68% CL) for double positron decay and lifetimes of 5.8×10^{21} yrs (68% CL) for positron electron capture decay, substantial work remains to be done to make these competitive with $\beta\beta$ decay.

Finally, it may be possible to push sensitivities down through the use of other cryogenic detectors. Garan* reported that considerable progress has been made during the last year in understanding the physics of metastable superconducting granulated detectors. These detectors seem to offer the possibility of low background measurements in double beta decay, solar neutrinos, and searches for monopoles and dark matter. It now seems possible to make energy measurements with these devices, rather than acting as integrating detectors above some threshold.

Perhaps the most interesting possibility is that of no ν $\beta\beta$ decay with Majoron emission. Measurements using a Time Projection Chamber with enriched ^{82}Se, ^{100}Mo, and ^{150}Nd samples[16] have observed an excess of events below the endpoint that might be consistent with Majoron emission with a branching ratio of a few x 10^{-4}. This is intriguing, as recent experiments using Ge detectors[17] have also seen an excess at about this level. The Moscow-Heidelberg group also sees an excess in their enriched ^{76}Ge detector. However, Piepke* has reported that after making a (large) background subtraction, the shape of the spectrum is not consistent with Majoron emission with an upper limit of 1.8 x 10^{-4} (90% CL) on the branching ratio. Further work is under way to study the origin of this excess.

NEUTRINO OSCILLATIONS

Theory

If the neutrino has a non zero mass and lepton number is also violated, then the physical neutrinos that we observe (e, μ, and τ) are not mass eigenstates. Instead there exist three mass eigenstates (ν_1, ν_2, and ν_3) with masses m_{ν_1}, m_{ν_2}, and m_{ν_3}. The three physical neutrinos are linear combinations of these mass eigenstates. For simplicity, one can consider the case of only two neutrinos, ν_e and ν_μ. Then, ν_e is predominantly composed of ν_1 with a small admixture (determined by a mixing angle θ between ν_1 and ν_2) of ν_2. It is then possible for ν_e to oscillate into ν_μ as it propagates. The probability for oscillation to occur is:

$$P(\nu_e \to \nu_\mu) = \sin^2 2\theta \, \sin^2[1.27 \times \Delta m^2(eV^2) \times L(m)/E_\nu(MeV)]$$

where $\Delta m^2 = |m_{\nu_2}{}^2 - m_{\nu_1}{}^2|$.

A variety of searches, both terrestrial and nonterrestrial, has been carried out and no definitive evidence for neutrino oscillations has been found in terrestrial experiments.[18]

Atmospheric Neutrinos

Cosmic rays (primarily protons and gammas) striking the upper atmosphere produce showers of pions and muons that decay, yielding ν_e and ν_μ with typical energies of around 1 GeV. The flux of these neutrinos can be calculated to about 30% accuracy and is sufficiently large that they can be observed in large underground detectors. By measuring the ratio of electron- to muon-neutrinos, one can search for neutrino oscillations in a manner that is relatively free of the individual flux uncertainties, as the ratio can be calculated to about 5% accuracy, as reported by Gaisser*. As the distance traveled by the neutrinos ranges from 10 to 10,000 km, one has sensitivity to small values of Δm^2 that are otherwise inaccessible.

Barloutaud* provided a review of measurements of atmospheric neutrinos have been carried out by a number of large underground detectors: Kamiokande and IMB (which are both large water Cherenkov detectors), Frejus, NUSEX, Baksan, and Soudan II (which are either scintillator based detectors or tracking calorimeters). In their analyses, they compare the observed ratio of ν_μ/ν_e divided by the Monte Carlo (MC) calculated ratio of ν_μ/ν_e. The results, as reported by Kielczewska* for IMB and Kaneyuki* for Kamiokande, are given in Table 2.

Table 2. Atmospheric neutrino data.

Group	ν_μ/ν_e(Data)/ν_μ/ν_e(MC)
Kamiokande[19]	$0.60\ {+0.07}/{-0.06} \pm 0.05$
IMB-3[20]	$0.54 \pm 0.05 \pm 0.12$
	$1.01 \pm 0.03 \pm 0.11$[a]
Frejus[21]	$1.06 \pm 0.18 \pm 0.15$
	$0.87 \pm 0.16 \pm 0.08$[b]
NUSEX[22]	$0.99\ {+0.35}/{-0.25} \pm ?$

[a] Stopping/through muons
[b] Fully contained events

The most sensitive of the detectors, Kamiokande and IMB, observe a signific nt deficit of the relative number of ν_μ compared to ν_e. The systematic uncertainties are 8% for Kamiokande and 22% for IMB (attributed mostly to uncertainties in the MC simulations). A possible explanation of this deficit may be attributed to neutrino oscillations. If so interpreted, the allowed range for the Kamiokande result is shown in Figure 1. IMB does not make any claim to observe neutrino oscillations, due to their much larger systematic uncertainties.

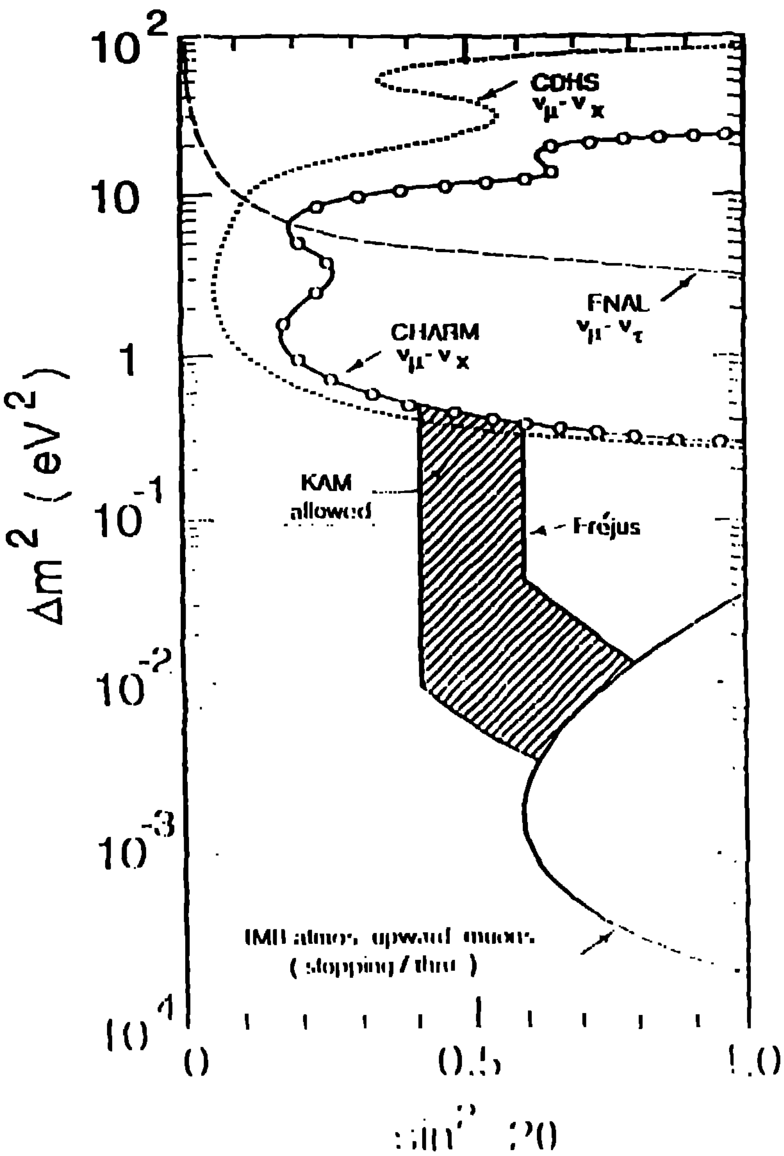

Figure 1. Range of neutrino oscillation parameters for atmospheric neutrinos allowed by the Kamiokande data. Also shown are limits set by atmospheric neutrino data from IMB and Frejus, as well as limits from accelerator searches for neutrino oscillations.

It may well be that the deficit is due to a systematic effect rather than new physics. Two major concerns have been raised. First, it is quite difficult to separate electrons from muons at low energies (a few hundred MeV) based on the differences in the observed rings. IMB and Kamiokande jointly plan to check this by building a 1 kiloton water Cherenkov detector at KEK by using beams of charged particles (π, μ, and e) to check the accuracy of the identification. It is also interesting that recently Soudan II, which is a tracking calorimeter, observed the same deficit, albeit with large statistical uncertainties at present. Second, there is possible concern that the cross sections used in the Monte Carlo calculations may be incorrect. These cross sections are calculated using the Fermi Gas Model (FGM), as the momentum transfer is low at these energies, and nuclear effects are important. But data recently published of measurements made at LAMPF of ν_μ cross sections on ^{12}C are at some variance with the FGM predictions.[23] Preliminary theoretical work apparently does not find any large differences with improved nuclear models.[24] It may be possible to check the cross sections by exposing the KEK test detector to a beam of low-energy neutrinos. This possibility is being investigated, but it will require upgrades of the accelerator and construction of a neutrino beam line, and so is unlikely to happen very soon.

Experiments at Reactors and Accelerators

In order to test the possibility that neutrino oscillations are being observed in measurements of atmospheric neutrinos (and solar neutrinos, as discussed below), a number of experiments have been proposed. Parke* reviewed the numerous possibilities for long baseline experiments that would be sensitive to Δm^2 range of 10^{-3} to 10^{-4} eV^2. All of these experiments would require either an upgrade to an existing accelerator and construction of new neutrino beam lines and/or construction of new large underground detectors. Perhaps the most plausible candidates for a long baseline experiment would involve an upgrade of the KEK accelerator and installation of a new neutrino beamline with the Super Kamiokande detector located 250 km away. Other plausible possibilities would involve Fermilab with an upgraded Soudan detector or CERN with the ICARUS detector. All of these experiments are designed to try to cover the region of allowed parameter space from the results of the atmospheric neutrino experiments. Bilenky* has pointed out the importance of searching for $\nu_\mu \to \nu_\tau$ oscillations. If one takes indications from the solar neutrino, atmospheric neutrino, and COBE results, together with the see-saw mechanism (in which neutrino masses are expected to scale as the square of the quark or lepton masses), then one might expect to observe $\nu_\mu \to \nu_\tau$ oscillations with small, but observable, mixing angles and values of Δm^2 in the few eV^2 range. Thus, the long baseline experiments are well justified by theoretical expectations.

Another class of experiments potentially able to shed some light on the atmospheric neutrino problem involves searching for neutrino oscillations using nuclear reactors as an intense source of antineutrinos. Mascaarenhas* reported on work underway at Cal Tech which would use the San Onofre reactor in California as the source with a 12-ton detector located 1 km away under about 20 meters water equivalent (mwe) of shielding. This experiment would use the $\nu_e + p \to e^+ + n$ reaction with a four-fold coincidence requirement of the prompt e^+ signal, the two annihilation gammas of the e^+, and the neutron capture gamma ray. Another possible experiment using the CHOOZ reactor in France was described by Kerret*. This experiment could take advantage of a large underground chamber with 300 mwe of shielding which exists at a distance of 1 km from the CHOOZ reactor, which is under construction and scheduled to come on line in 1996. This experiment would employ an 8-ton Gd-loaded scintillator and be sensitive to neutrino oscillations down to a Δm^2 of about 10^{-3} eV^2. Finally discussions are underway to carry out an experiment with a new large scintillation detector to be located in the old IMB proton decay chamber at the Morton Salt Mine in Ohio.[25] This experiment would use the Perry reactor, which is at a distance of 13 km from the IMB site, as the source of antineutrinos. The detector would be a 1-kiloton scintillator detector and would be sensitive to neutrino oscillations down to a Δm^2 of about 10^{-4} eV^2.

Finally, the importance of $\nu_\mu \to \nu_\tau$ oscillations is being addressed by the NOMAD experiment at CERN, as presented by Levy*. This type of oscillation is favored with a ν_τ mass in the range of 1 eV if the solar neutrino experiments are indicating oscillations of $\nu_e \to \nu_\mu$ and the seesaw model is correct. The detector, which is a large tracking detector consisting of drift chambers followed by a total radiation detector and muon chambers, coupled with a decay in flight neutrino beam will be capable of reaching limiting values of Δm^2 of about 0.4 eV^2 and mixing angles with $\sin^2 2\theta$ of about 4×10^{-4} (90% CL). This more or less encompasses the region of parameter space expected for $\nu_\mu \to \nu_\tau$ oscillations if the solar neutrino and atmospheric neutrino results are in fact indicative of neutrino oscillations and if the see saw mechanism is the correct model for determining how the masses of the neutrino generations scale.

SOLAR NEUTRINOS

Perhaps the most outstanding discrepancy between prediction and measurements in current particle physics comes from the solar neutrino problem, in which the radiochemical chlorine experiment of Davis et al. observes a deficit of high-energy neutrinos of a factor of four.[26] This experiment is sensitive primarily to the ^{7}Be and ^{8}B neutrinos produced by fusion reactions in the Sun. A deficit of a factor of two of the ^{8}B neutrinos has been confirmed by the Kamiokande (K III) experiment, as reported by Kaneyuki*. Kamiokande II (III) is an upgraded version of a large real-time water Cherenkov detector that was originally built to search for proton decay. The observed deficits appear to be statistically quite significant with small systematic errors, so that the ratio of the measured rate compared to the Bahcall-Pinsonneault Standard Solar Model (SSM)[27] predictions are: $\phi(Cl)/SSM = 0.23 \pm 0.02 \pm 0.03$ and $\phi(KII)/SSM = 0.49 \pm 0.04 \pm 0.06$. Different SSM give somewhat different predictions. For example, using the Turck-Chieze et al[28] SSM, $\phi(Cl)/SSM = 0.23 \pm 0.02 \pm 0.03$ and $\phi(KII)/SSM = 0.63 \pm 0.05 \pm 0.08$. While the differences are appreciable, they are still insufficient to resolve the problem. However, the predicted fluxes are extremely temperature dependent, as the ^{8}B (^{7}Be) flux scales with the core temperature of the Sun (T_c) as $\phi(^{8}B) \propto T_c^{18}$ ($\phi(^{7}Be) \propto T_c^{8}$). Thus, a 5% decrease in T_c can lower the fluxes to be in agreement with the observations.

Pinsonneault* presented the results of the most recent SSM calculations. These now include the effects of helium diffusion, opacities which are in better agreement with helioseismology data, updated Fe abundances, and better atomic physics calculations. The Bahcall Pinsonneault results have not changed appreciably from earlier models, while the updated results of the Turck Chieze et al model is now in closer agreement to the Bahcall Pinsonneault. Still, all is not perfect with the models. Pinsonneault noted that the measured abundances of ^{7}Li and CNO isotopes in the convective zone are in strong disagreement with the SSM predictions. Pinsonneault felt that the likely source of this difference was due to effects of rotation and mixing, which are not included in the SSM. Preliminary work to incorporate these effects indicate that it is likely that the prediction of the abundances will come closer in line with observations while the maximal effect on the ^{8}B neutrino flux is a decrease of 7%.

Morrison* and Kocharov* discussed many of the possibilities which have been proffered to show that the solar neutrino problem does not exist. Many Nonstandard Solar Models have been invoked to try to lower the core temperature of the Sun, incorporating effects such as turbulent diffusion, massive mass loss, strong magnetic fields, a burnt-out core, etc. However, all of these models have run into problems in trying to reproduce other measured parameters (e.g., the luminosity) of the Sun. Other explanations offered by Morrison included incorrect nuclear cross sections, the need to use selected subsets of data from the solar neutrino experiments which are in better agreement with the SSM predictions, and other possibilities too numerous to list. However, subsequent speakers addressed essentially all of the concerns raised and the general consensus was that the solar neutrino problem is real.

Other explanations to resolve the solar neutrino problem involving new physics (such as Weakly Interacting Massive Particles (WIMP's), neutrino magnetic moments, neutrino decay, neutrinos oscillations, etc. have also been proffered. Petcov* reviewed the status of theoretical work on MSW oscillations[29], vacuum oscillations[30], and solutions involving magnetic moments of the neutrino[31]. Akhmedov* demonstrated the possibility of $\nu \rightarrow \bar{\nu}$ oscillations via natural mechanisms which exist within the Sun involving a handedness to the magnetic fields due to the rotation of the Sun. Nunokawa* discussed neutrino spin precession with flavor mixing as a possible solution to the solar neutrino problem and concluded that this mechanism cannot yet be ruled out. Pal* discussed neutrino interactions in matter which might ultimately be of interest in solar neutrino studies, although the effects are quite small compared to current sensitivities. Finally, Halprin* discussed the possibility that neutrino oscillations could occur even in the case of massless neutrinos through a flavor changing gravitational interaction and used the current results of the solar neutrino experiments to rule out part of the parameter space for this type of interaction.

Most of the explanations involving new physics have been ruled out or disfavored by either laboratory or astrophysical measurements. While vacuum oscillation and magnetic moment solutions are still possible, it appears that perhaps the most likely particle physics solution is that of matter enhanced neutrino oscillations, the Mikheyev Smirnov

Wolfenstein (MSW) oscillations. In order to try to resolve the source of the deficit, two radiochemical gallium experiments, SAGE (Soviet-American Gallium Experiment) and GALLEX (GALLium EXperiment) were mounted. The threshold of the gallium experiments is sufficiently low that it is sensitive to the dominant flux of low-energy p-p neutrinos, which are produced in the primary energy producing reaction of the Sun, the fusion of two protons. The flux of the p-p neutrinos is determined to about 2% accuracy in a relatively model independent manner and is directly coupled to the measured solar luminosity. The gallium experiments have now announced their first results, and also find a significant deficit. Bowles* reported that SAGE finds the deficit (compared to the Bahcall-Pinsonneault SSM) to be $\phi(\mathrm{SAGE})/\mathrm{SSM} = 0.44 +0.13/-0.18 \pm 0.11$ while Stolarczyk* reported that GALLEX observes $\phi(\mathrm{GALLEX})/\mathrm{SSM} = 0.62 \pm 0.13 \pm 0.06$. Spiro* showed analyses demonstrating that the runs in the three radiochemical experiments are all distributed statistically, as expected. Thus, as the results of these two experiments appear to be Poisson distributed and are dominated by statistical uncertainties, Spiro* felt it seems reasonable to take a weighted average to obtain $\phi(\mathrm{Ga})/\mathrm{SSM} = 0.55 \pm 0.11$ as the result of the combined gallium experiments. If one assumes only that fusion reactions power the Sun and that the Sun is in thermal equilibrium, one expects a minimal rate in the Ga experiments of 0.60 SSM. A rate significantly lower than this would require one to invoke new physics, rather than a change in the astrophysical models of the Sun, as the solution to the solar neutrino problem. Thus, while the Ga experiments seem to favor a particle physics solution, they are not yet precise enough to definitely rule out an astrophysics solution. In addition, it will be important to check the quoted efficiencies of the gallium experiments using an artificial neutrino source. Both SAGE and GALLEX are planning to do this with intense ^{51}Cr sources. However, using the results of the four experiments, a recent analysis[32] indicates that any model invoking a cooler Sun is ruled out at the 99.99% CL. All four experiments are consistent with the hypothesis of MSW oscillations, and the regions in the parameter space of Δm^2 versus $\sin^2 2\theta$ are shown[32] in Figure 2. There are two allowed solutions, the one with $\sin^2 2\theta \sim 10^{-2}$ is called the nonadiabatic solution, while the one with $\sin^2 2\theta \sim 0.6$ is called the large mixing angle solution. These solutions differ in their prediction of the energy dependence of the effect of oscillations on the solar neutrino spectrum.[32] The nonadiabatic solution gives strong suppression of the ^7Be and

^{8}B neutrinos but leaves the p-p neutrinos essentially unaffected. The large mixing angle solution provides for a roughly equal suppression of neutrinos at all energies.

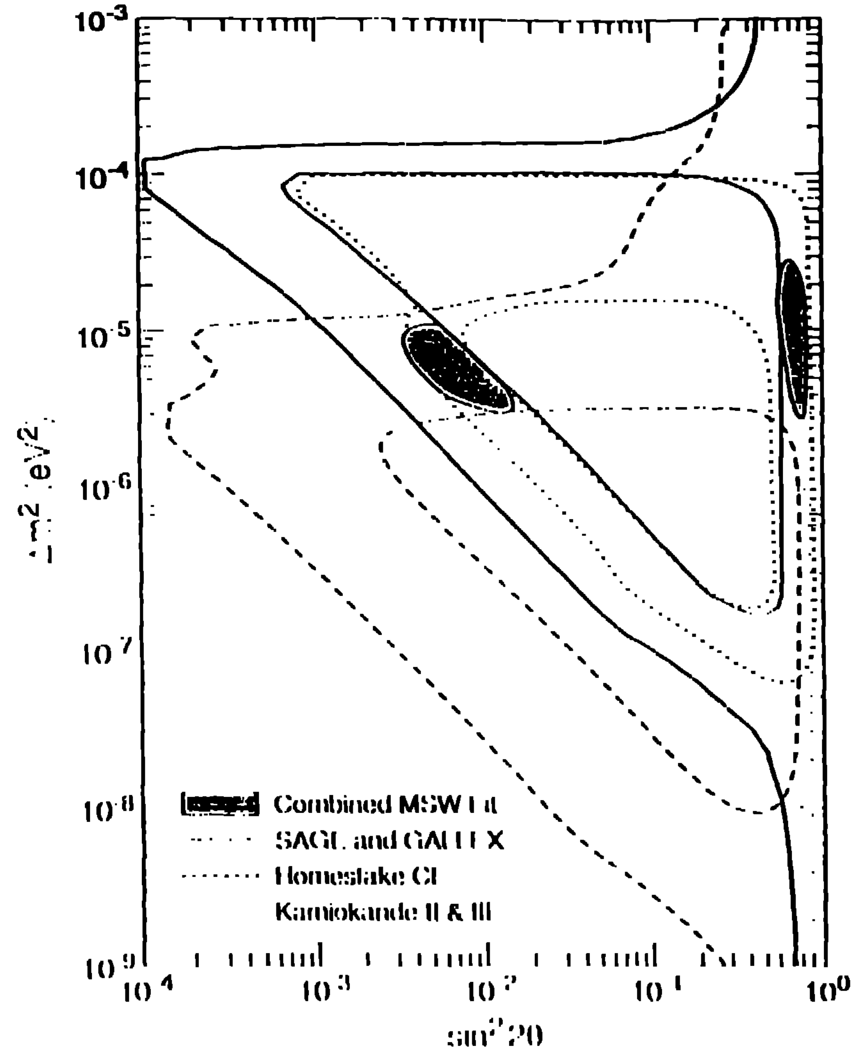

Figure 2. Allowed region of neutrino oscillation parameters for solar neutrinos. The limits set by the chlorine, Kamiokande, and combined gallium experiments are as indicated by the inset legend.

In order to determine the origin of the solar neutrino problem, it now appears that model independent tests must be made. This could done by either directly measuring the solar neutrino spectrum and looking for the distortions predicted by the MSW oscillations, or to measure the flux of ν_e and compare it to measurements of the total flux of $\nu_e + \nu_\mu + \nu_\tau$. Four experiments to do this are either under way or working on prototype development. The Sudbury Neutrino Observatory (SNO) experiment, as reported by B. Robertson[4], is a large water Cherenkov detector using 1 kiloton of heavy water (D_2O). In this experiment, one will be able to directly measure the ^{8}B neutrino spectrum by observing the energetic electron emitted in the charged current (CC) reaction $\nu_e + d \rightarrow p +$

$p + e^-$. In addition, one can measure the total flux of all neutrinos above a 2.2-MeV threshold by observing the neutron created in the neutral-current (NC) reaction $\nu_e + d \rightarrow p + n$. While the canonical plan to detect neutrons in SNO is by adding 2.5 tons of NaCl and observing the gamma from neutron capture on the Cl, work is underway to develop ultra low background ^{3}He proportional counters to provide neutron detection, as reported by H. Robertson*. Finally, in SNO one can also observe the elastic scattering (ES) reaction $\nu_e + e^- \rightarrow \nu_e' + e^-$. In the Super-Kamiokande project, as reported by Kaneyuki*, a 50-kiloton water Cherenkov detector will be built to study the elastic scattering (ES) reaction. This experiment will give rates almost 100 times higher than Kamiokande and will be able to measure the ^{8}B neutrino energy spectrum from the recoil electron spectrum. The SNO and Super-Kamiokande projects expect to come on the air in the fall of 1995 and spring of 1996, respectively. In another detector under development, the Borexino project[33] would use 300 tons of scintillator viewed by an array of photomultipliers to directly observe the ^{7}Be neutrinos via the ES reaction. This experiment is under development and hopes to come on line about 1996. Finally, a 3-ton prototype of a liquid argon time projection chamber has demonstrated the feasibility of full track reconstruction over drift distances of a few meters, as reported by Montanari*. Thus, this detector looks quite a lot like an electronic bubble chamber in its ability to reconstruct tracks and identify particles. Plans are now under way to use this technique in a 5-kiloton ICARUS detector, which would detect ^{8}B solar neutrinos primarily by the ES reaction. These experiments will provide real-time information with better resolutions, lower backgrounds, and count rates almost 100 times higher than previous solar neutrino experiments. One thus expects that they should be able to determine the origin of the solar neutrino problem in a model-independent manner before the end of this decade.

One detection scheme for solar neutrinos, proposed by Weber, that involves use of coherent scattering from sapphire crystals to detect solar neutrinos, seems not to be feasible. Measurements by McHugh* of the scattering of solar neutrinos from sapphire crystals mounted on a water balance indicate an absence of coherent effects, with a limit of about 2% (68% CL) of that expected. It appears the cross sections are incoherent for scattering from crystals, which results in cross sections reduced by many orders of magnitude from that for coherent scattering, thus rendering a solar neutrino experiment impossible.

SUPERNOVA NEUTRINOS AND DARK MATTER

The dark matter problem, in which more than 90% of the Universe is comprised of some unknown (nonbaryonic) form of matter was reviewed by Caldwell* with some additional discussion by Krauss*. The need for dark matter now seems to be well established and intensive experimental efforts are underway to determine the origin of the dark matter. Searches for MAssive Compact Halo Objects (MACHOs) are underway by three groups using the gravitational microlensing technique. Initial tests indicate they have sufficient sensitivity to observe objects with masses greater than 10^{-7} solar masses in the halo of our galaxy. One year of observations are now being analyzed and within the next year or so we should know if MACHOs are a dominant form of dark matter. The recent observations of COBE (COsmic Background Explorer) and IRAS (InfraRed Astronomical Satellite) seem to indicate the need for about 20-40% of hot dark matter mixed in with cold dark matter in order to reproduce the observed large scale structure of the Universe. A prime candidate for the hot dark matter is a tau neutrino with a mass of about 7 eV. Axions are also still a dark matter candidate and efforts are under way to build a large cryogenic cavity inside a superconducting magnet which would allow detection of axions by their coupling to the magnetic field. Weakly Interacting Massive Particles (WIMP's) have been largely ruled out as dark matter candidates by experiments using ultra low background solid state detectors in which a WIMP would be detected by observation of the recoil nucleus when the WIMP's scatter in the detector. Finally a number of efforts are under way using cryogenic detectors which have the potential of being able to observe the nuclear recoils from neutralinos (the lightest stable SUperSYmmetric particle) scattering in the detectors. Thus, it is hoped that the origin of dark matter may be determined within the next decade.

If the tau neutrino has a mass in the few eV range, as possibly indicated by COBE and IRAS, it is of crucial importance to find a means to measure such a mass. Neutrino oscillations, such as the NOMAD experiment, provide one means to probe this mass range. However, a more direct means is by studies of the neutrinos emitted in supernova explosions, as discussed by Krauss*. A great deal of detailed modeling of supernovas has now been carried out and the question of the effect of a non zero neutrino mass has been looked into. If a supernova goes off in our galaxy during the operating lifetime of SNO and Super Kamiokande (and any other large detectors which are operational), the count rates that one expects to see are of order 10^3 events in SNO and 10^4 events in Super Kamiokande. With such high statistics, the detailed evolution of the neutrino pulse can be studied. It appears that both model-dependent and model-independent effects of a non zero neutrino mass should be observable for masses of tens of eV. Studies also indicate, although with less reliability, that it may be possible to determine neutrino masses as low as a few eV. Thus, there is some hope that a nearby supernova may provide the best information on a possible tau neutrino mass in the few eV to few tens of eV range.

CONCLUSIONS

At present, laboratory measurements are all consistent with the hypothesis that neutrinos are massless. In particular, there is not a 17 keV neutrino. Nonetheless, extensions beyond the Standard Model generically predict non zero neutrino masses. There are possible indications of new physics in no n bb decay with emission of a Majoron with a branching ratio of around 10^{-4}. However, while an unexplained excess of events below the endpoint is observed in all of the experiments, the data are probably inconsistent with Majoron emission. There appear to be systematic effects in the tritium beta decay experiments which are not completely understood. The consistent observation of a best fit of negative m_ν^2 could possibly indicate the presence of new physics, but a great deal of work remains to be done before one can seriously consider new physics as the solution to this problem. Possible evidence for neutrino oscillations is observed in atmospheric neutrinos and solar neutrinos. In the case of atmospheric neutrinos, only one experiment has the sensitivity to claim consistency with neutrino oscillations. A number of possible systematic effects may also account for the observations, and further studies are under way. In the case of solar neutrinos, four experiments all see significant deficits below the rates predicted. Various analyses indicate it is unlikely that changes to the Standard Solar Models can accommodate the results. The most likely consistent explanation is that we are observing matter-enhanced MSW neutrino oscillations. Yet, given the extreme dependence of the neutrino fluxes on the core temperature of the Sun, it is difficult to definitively rule out astrophysical solutions. But a new round of experiments will provide model-independent tests, which should provide the solution to the solar neutrino problem in the next five to seven years. Finally, measurements of the 3 K microwave background radiation seem to favor that some fraction of the dark matter may be comprised of a (tau) neutrino with a mass of several eV. If the large solar neutrino detectors now under construction should be lucky enough to observe a supernova within our galaxy during their lifetimes, it may be possible to address the question of a tau neutrino mass of several eV.

It is clear that the new round of experiments under construction and being discussed will greatly impact our understanding of neutrino mass and mixing. If we are fortunate, the early indications we are seeing with the present round of experiments will be borne out with new data by the end of this decade. It may well be that these experiments are providing us with the first window to the long-sought new physics beyond the Standard Model.

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